ONBOARD IMAGE PROCESSING

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ABSTRACT

This paper considers the possibility of onboard geometric correction of Thematic Mapper type imagery to make possible image registration. Typically, image registration is performed by processing raw image data on the ground. The geometric distortion (e.g., due to variation in spacecraft location and viewing angle) is estimated by using a Kalman filter updated by correlating the received data with a small reference subimage, which has known location. Onboard image processing dictates minimizing the complexity of the distortion estimation while offering the advantages of a real-time environment. In keeping with this, the distortion estimation can be replaced by information obtained from the Global Positioning System and from advanced star trackers. Although not as accurate as the conventional ground control point technique, this approach is capable of achieving subpixel registration. Appropriate attitude commands can be used in conjunction with image processing to achieve exact overlap of image frames. The paper investigates the magnitude of the various distortion contributions, the accuracy with which they can be measured in real-time, and approaches to onboard correction.

The Thematic Mapper scans a succession (16 at a time) of lines on the earth, each of which is 185 kilometers long. This is accomplished by optically focusing the light from the scene and sweeping it across a row of small individual photodetectors. The scanning action is continuously repeated with the spacecraft motion causing successive scans to lie a fixed distance from each other.

A user of images produced by Thematic Mapper is likely to be interested in some particular kind of geologic, agricultural, urban, or other feature of the scenes being analyzed. In performing this analysis, it is frequently desirable that two images of the same scene be registered; that is, each physical part of the scene is in the same location on the two images so that the picture elements (pixels) of the two images can be aligned. Such precision is not easy to attain, mainly because of varying distortions and viewing conditions from one image to the next. (See Figure 1.)

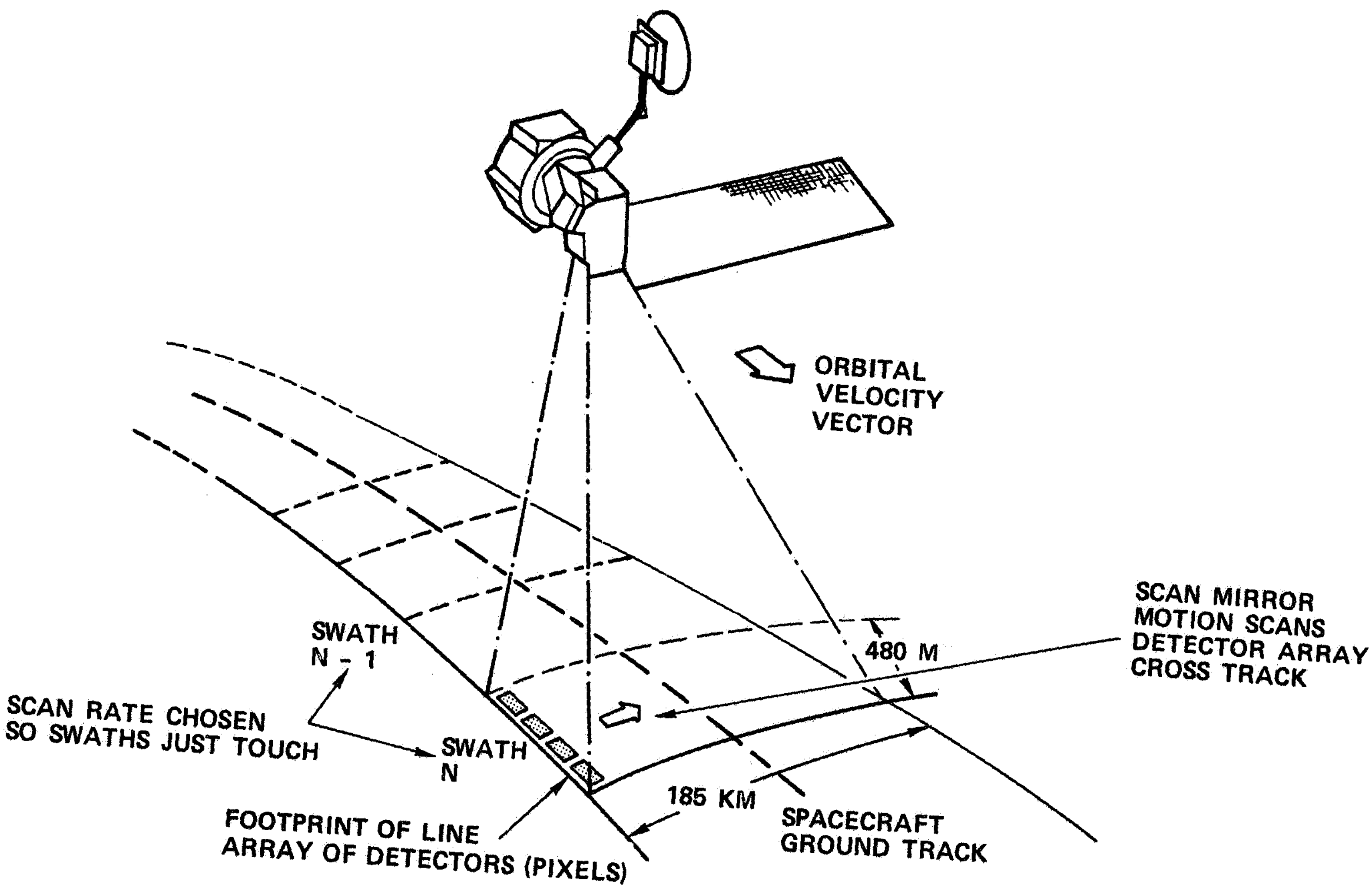


Figure 1. Multispectral Scanning Sensor Geometry

Registration is accomplished by estimating the sources of distortion and performing geometric correction to compensate for the distortion. The ultimate registration error is therefore primarily determined by the accuracy of the distortion estimation, not by its actual magnitude. The levels of registration differ by the amount of processing required. Isodistance requires constant interpixel distances and parallel scan lines in images of the same region. However, different images of the same region have an unknown relative displacement which is generally not an integer number of pixels. Absolute location of pixels specifies the relative displacement of different images and must be an integer number of pixels. Exact overlap of image frames require the same distortion information as absolute location registration; however it requires that the geometric correction produce image frames with exactly corresponding pixel locations. Map projection includes the previous levels of registration in addition to correcting the distortion caused by factors not associated with the satellite (e.g., earth curvature and rotation). (See Figure 2.)

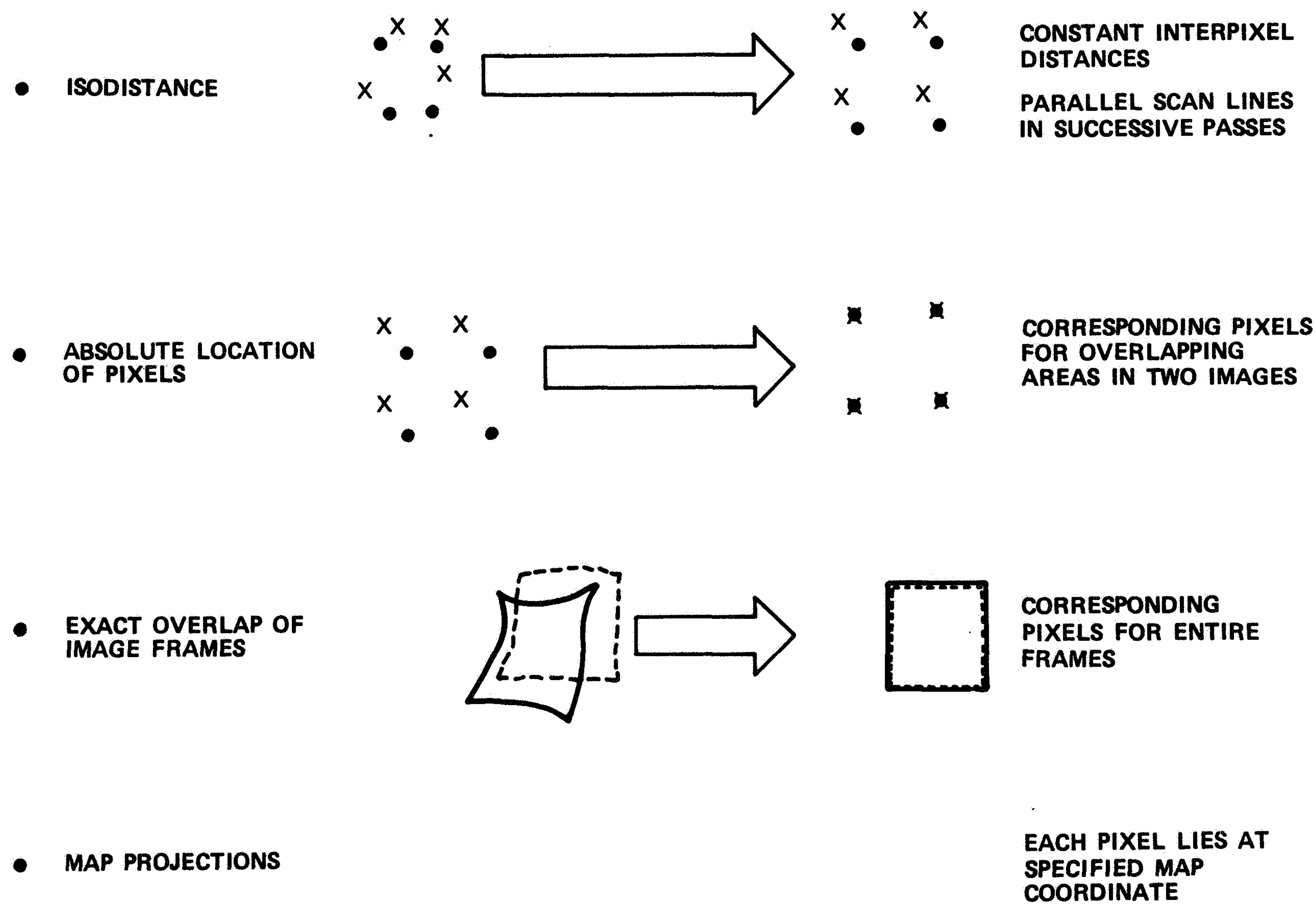


Figure 2. Registration Levels

The location of the spacecraft with respect to the ground at a given time of day can vary significantly for different passes over a region. Pixels compared at the same time of day for subsequent passes, with no knowledge of spacecraft location, can cause significant offset in pixel location. Absolute location registration requires that this offset be known and corrected and is essential if different images of the same region are to be compared. (See Figure 3.)

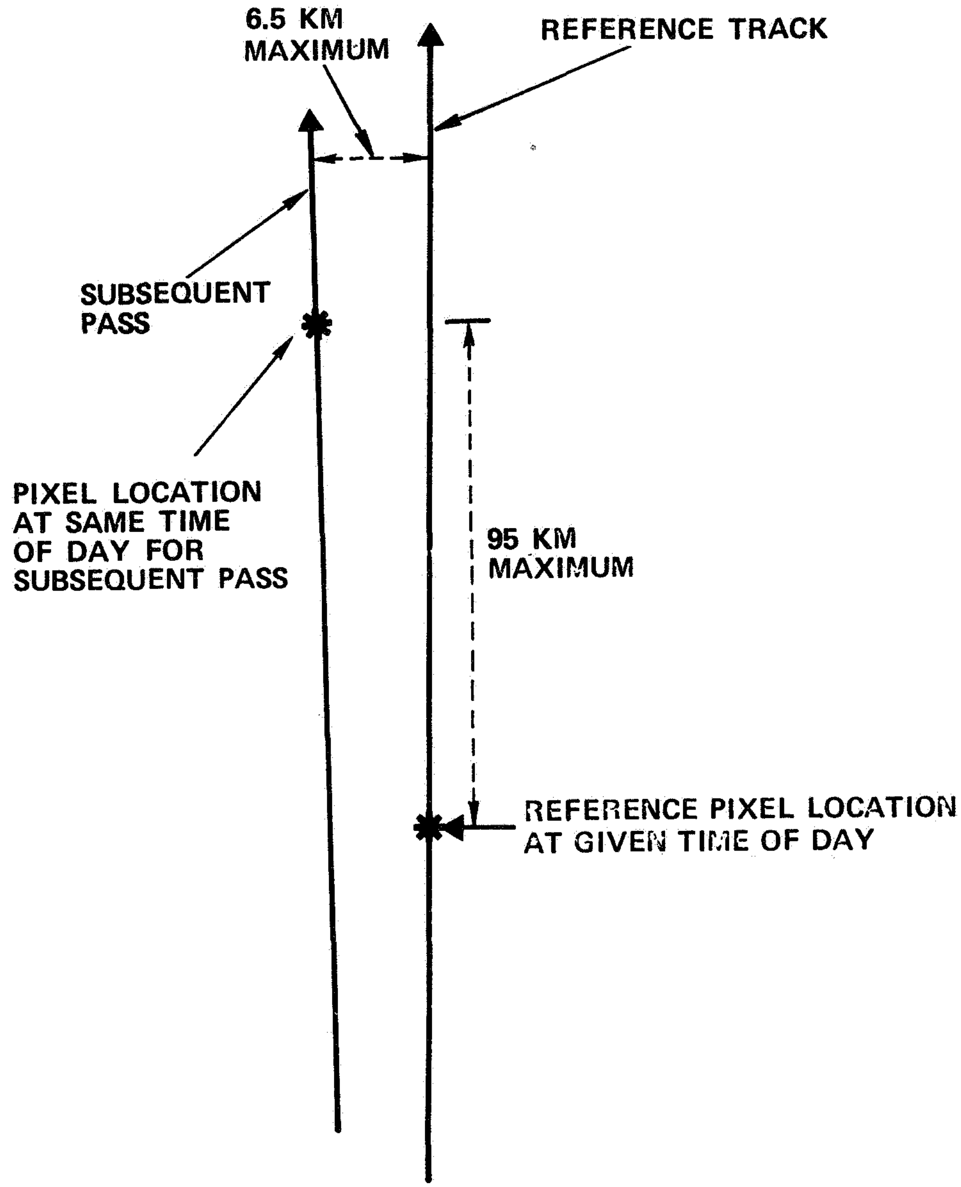


Figure 3. Absolute Location Ephemeris Distortion

Variation in the spacecraft altitude for different passes over a region affects pixel spacing in the cross track direction for both isodistance and absolute registration. Except for the effect of variation in the orbital velocity, the difference in the spacecraft's along track and cross track position has no impact on isodistance distortion. The altitude and orbital velocity of the spacecraft changes very little in comparison to the cross track drift for different passes over a region. Consequently, isodistance distortion caused by ephemeris variation is far smaller than the corresponding absolute distortion. (See Figure 4.)

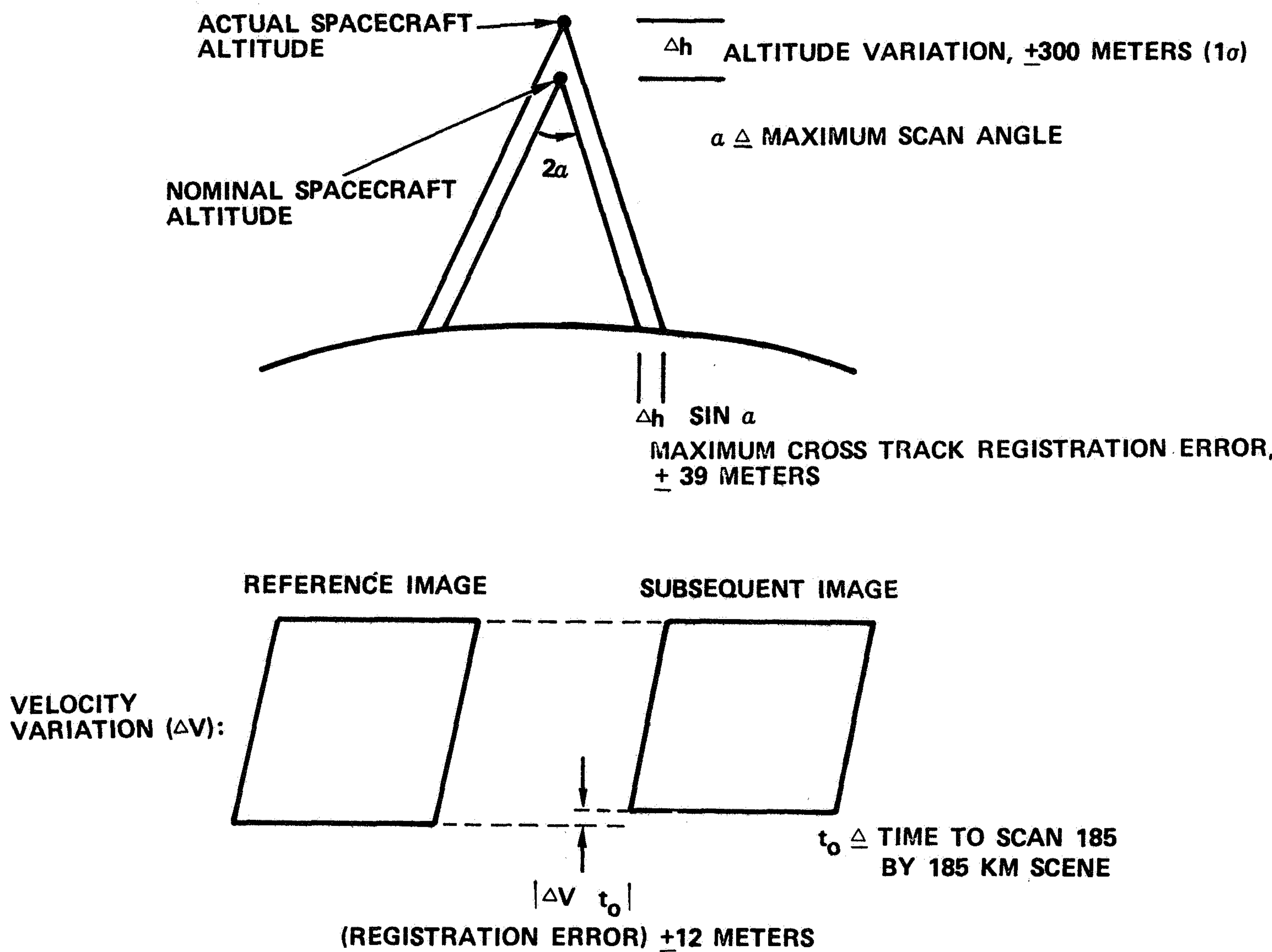


Figure 4. Isodistance Ephemeris Distortion

The scanning motion of the Thematic Mapper must be precisely the same on subsequent passes over a region if no distortion is to be introduced. Variation in the active scan duration (i.e., scan velocity) will cause stretching (or compression) of the pixel spacing within a scan line. Variation in the scan period will cause the spacing between scan lines to be different for subsequent images of a region, causing different images of the same region to have a different number of scan lines. (See Figure 5.)

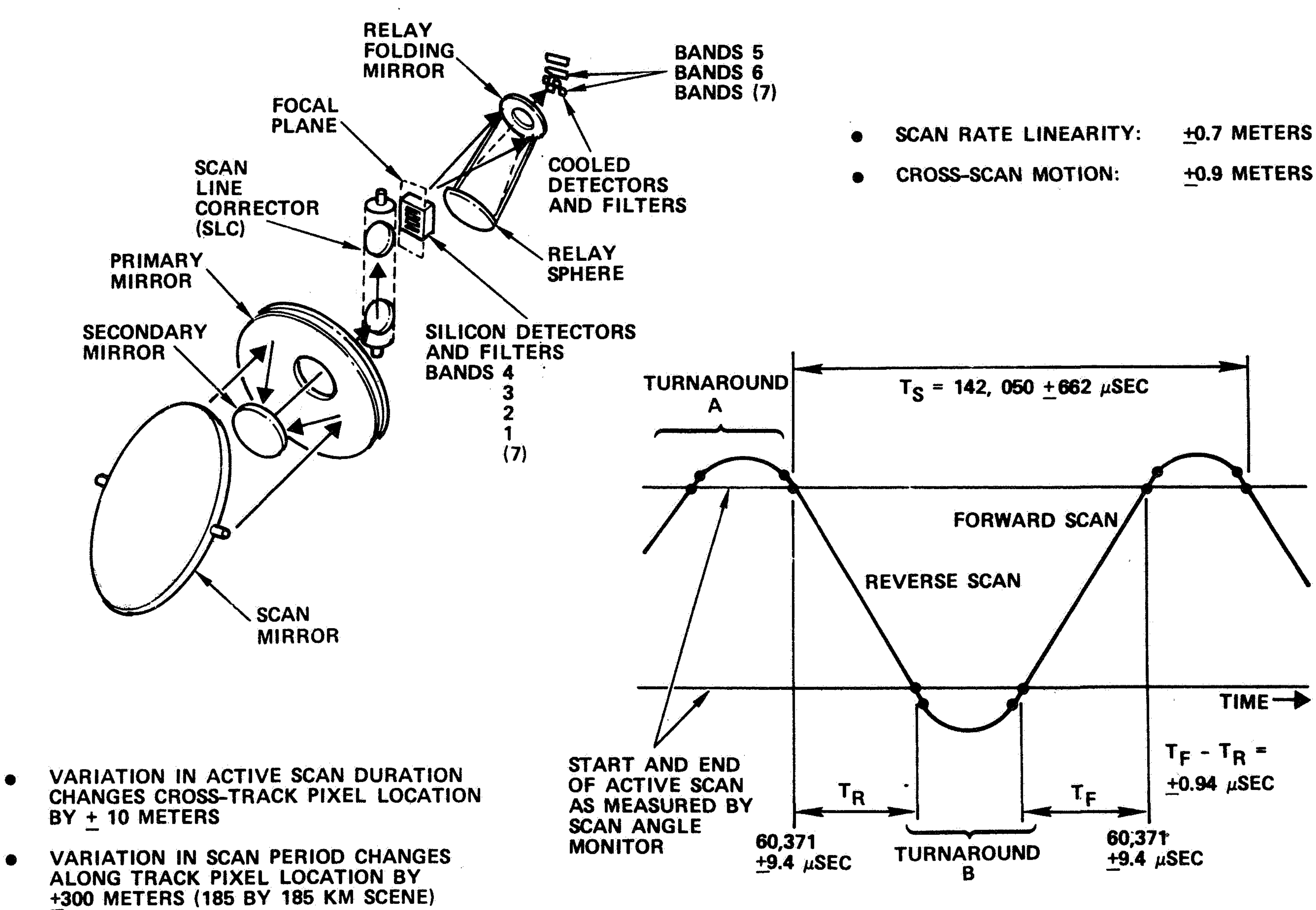


Figure 5. Thematic Mapper Scan Distortion

The spacecraft is assumed to be in an earth-pointing attitude mode. Variation in the absolute attitude of the spacecraft with respect to a previous pass will cause an absolute location registration error proportional to this attitude variation. Such variation is limited by the accuracy of the star tracker. Isodistance registration requires a stable attitude reference during the scene, but is relatively unaffected by the absolute accuracy of this reference. Consequently, isodistance registration is primarily determined by the gyro drift in the stellar-inertial attitude reference system. (See Figure 6.)

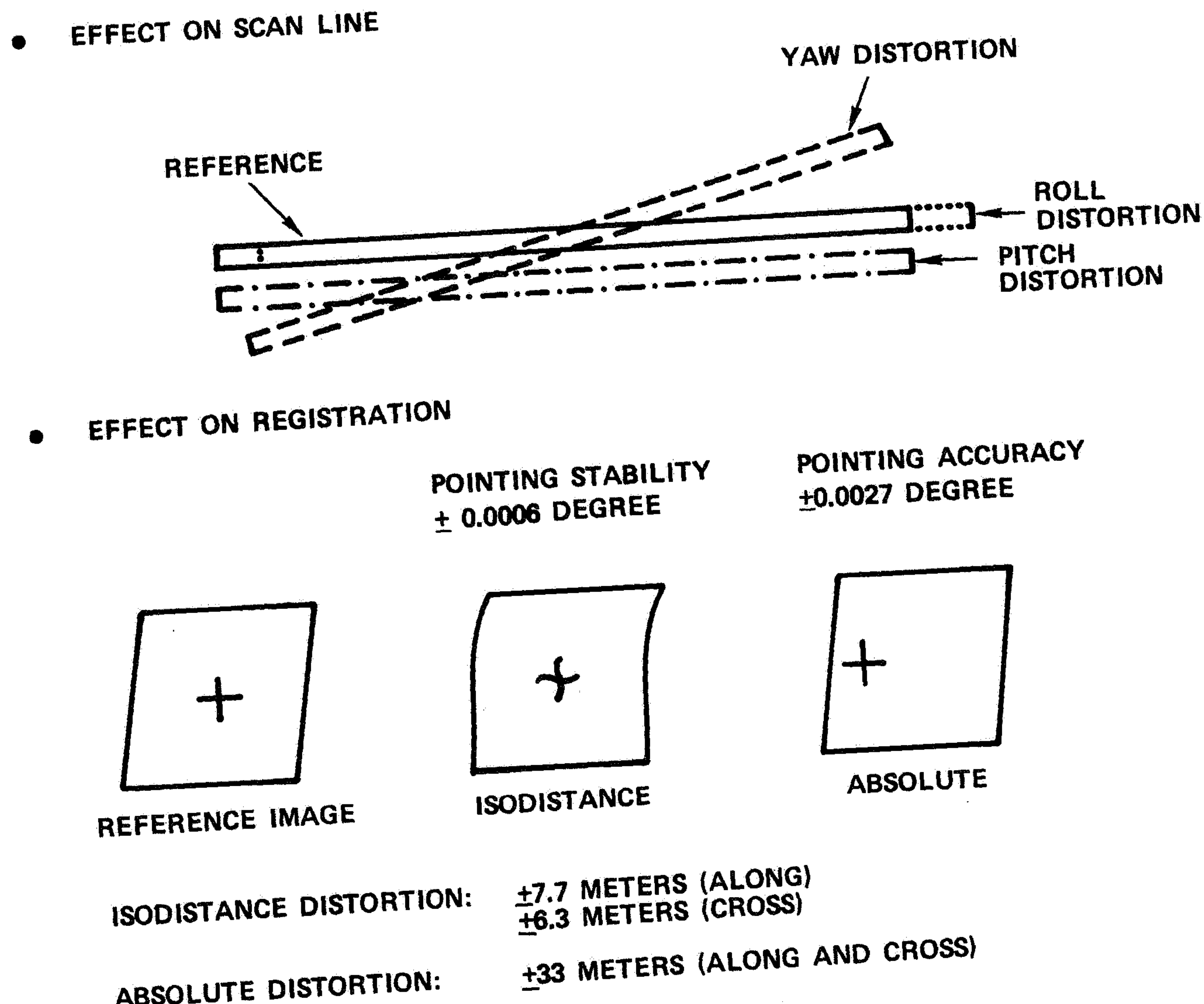
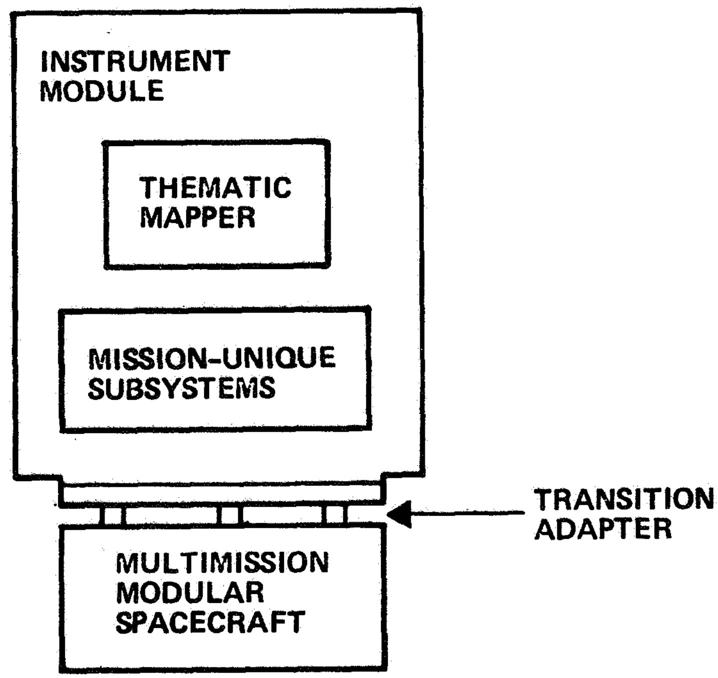


Figure 6. Attitude Distortion

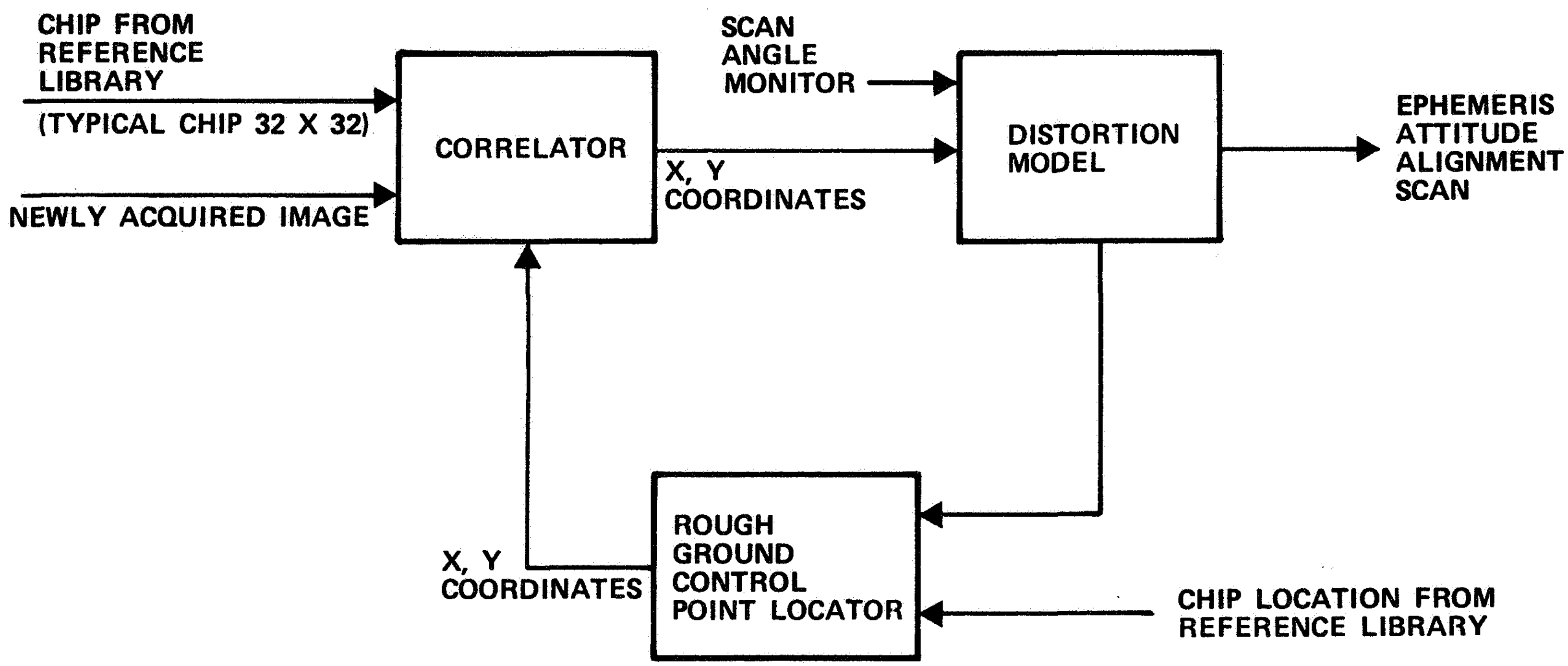
For the reasons previously cited, the attitude of the Thematic Mapper must be held constant (with respect to the earth-pointing frame of reference) to prevent distortion. However, the coordinate axes of the Thematic Mapper are not the same as those of the Attitude Control System. The difference between these sets of axes exhibits both long term drift and a short term sinusoidal variation at the orbital frequency due to thermal effects. The relative alignment of the Thematic Mapper and the Attitude Control System must be determined and the appropriate geometric correction performed. (See Figure 7.)



- MUST KNOW ATTITUDE OF THEMATIC MAPPER RELATIVE TO MMS ATTITUDE REFERENCE
- ALIGNMENT CONSISTS OF SLOWLY VARYING BIAS COMPONENT AND APPROXIMATELY SINUSOIDAL THERMAL COMPONENT
- ABSOLUTE DISTORTION: ± 34 METERS (ALONG AND CROSS)
- ISODISTANCE DISTORTION: ± 4.4 METERS (ALONG)
± 1.0 METERS (CROSS)

Figure 7. Alignment Distortion

The technique usually employed to estimate distortion on the ground uses ground control points which consist of 32 by 32 pixel subimages with known location. The received imagery is correlated with the ground control point to determine the proper position of one pixel. A dynamic model is used for the distortion, with the correlation information serving as observations of the distortion process. By using Kalman filtering, the distortion at each pixel in the image can be estimated and corrected. Variations in the scan duration occur at a higher frequency than can be measured by ground control points; consequently, scan distortion must be measured by the Scan Angle Monitor. (See Figure 8.)



- VALUE: VIRTUALLY ELIMINATES DISTORTIONS THAT CHANGE SLOWLY COMPARED TO GCP FREQUENCY
- ASSUMPTIONS: GCP HAS FIXED APPEARANCE
- COST: MEMORY, COMPLEXITY

Figure 8. Use of Ground Control Points

The location and velocity of the spacecraft can be determined to ±5 meters and ±0.3 meters per second (one-sigma), respectively, by using the Global Positioning System. The isodistance registration error depends on the velocity uncertainty over the duration of a scene (approximately 30 seconds). The GPS velocity uncertainty has less impact on pixel spacing over the scene duration than does the GPS location uncertainty. The attitude of the spacecraft is determined by the attitude control system. The absolute attitude accuracy is consequently limited by the stellar-inertial attitude reference, which is assumed to use a star tracker of advanced design. The isodistance attitude error is determined by the stability of the spacecraft's attitude during a scene, not by its absolute pointing accuracy. Alignment can be calibrated every few days from the ground using ground control points. Isodistance registration requires the scan lines to be parallel for different images of a region; as a result the alignment error due to yaw is the same for both absolute and isodistance registration. Scan distortion must be estimated from the Scan Angle Monitor information. Because of the high frequency content of the scan distortion, it also has the same impact on isodistance and absolute registration. (See Figure 9.)

DISTORTION SOURCE	ESTIMATION TECHNIQUE	ONE-SIGMA ERROR (EACH AXIS)	
		ABSOLUTE (METERS)	ISODISTANCE (METERS)
EPHEMERIS	GLOBAL POSITIONING SYSTEM	5	1
SCAN	SCAN ANGLE MONITOR	1.6	1.6
ATTITUDE	STELLAR-INERTIAL REFERENCED ATTITUDE CONTROL SYSTEM	10	3.3
ALIGNMENT	PERIODIC CALIBRATION FROM GROUND	5	5
RSS		12.4	6.3

Figure 9. Distortion Estimation Without GCPS

The onboard real-time environment dictates that processing and data storage be kept as small as possible. However, in order for the processing to be useful, it must meet certain minimum requirements in terms of registration accuracy. Absolute registration accuracy in the 0.5 to 0.3 pixel range can be achieved without the use of ground control points. Isodistance registration accuracy of 0.2 pixel is also achievable. Improvement in absolute registration accuracy to less than 0.2 pixel (one-sigma) can be obtained with the use of ground control points; however, this requires a very sophisticated distortion model in addition to the large number of ground control points. Processing considerations therefore indicate that ground control points be avoided if acceptable registration performance is achieved without them. (See Figure 10.)

- PROCESSING COMPLEXITY
  - WITH GCP'S
    - KALMAN FILTER ($\sim$20 STATES)
    - GCP CORRELATION
    - SCAN ANGLE MONITOR READOUT
  - WITHOUT GCP'S
    - SCAN ANGLE MONITOR READOUT
    - GPS
    - ADVANCED STAR TRACKER
- DATA STORAGE REQUIREMENTS
  - WITH GCP'S
    - AT LEAST SEVERAL SCANS
    - POSSIBLY SEVERAL ENTIRE IMAGES (INCREASED ACCURACY)
    - CONTROL POINT LIBRARY
  - WITHOUT GCP'S
    - FEW SCANS AT MOST
- PERFORMANCE

  GCP'S IMPROVE REGISTRATION

Figure 10. Tradeoffs in Distortion Measurement

Ephemeris adjustment is employed infrequently because of limitations in the propellant capacity. Large cross track drifts can be corrected by performing ephemeris adjustment once every 16 days. Because of the response time of the attitude control system, attitude commands can be used at most only a few times per orbit. This is sufficient to minimize the data storage requirement by maintaining the scan lines to be roughly parallel to the reference scan. Also, by pointing cross track, attitude commands can facilitate the exact overlap of image frames. The remaining geometric correction is performed by resampling the pixel intensities to achieve the desired output matrix. Resampling consists of locating the position of a desired pixel in the scanned image and interpolating to determine its intensity. (See Figure 11.)

- EPHEMERIS ADJUSTMENT
    - COMPENSATE FOR CROSS TRACK DRIFT
- ATTITUDE COMMANDS
    - COMPENSATE FOR ALIGNMENT ERRORS
    - EXACT FRAME OVERLAP
- RESAMPLING
    - COMPENSATE FOR SCANNER ERRORS
    - COMPENSATE FOR EPHEMERIS
    - COMPENSATE FOR ATTITUDE CONTROL ERRORS

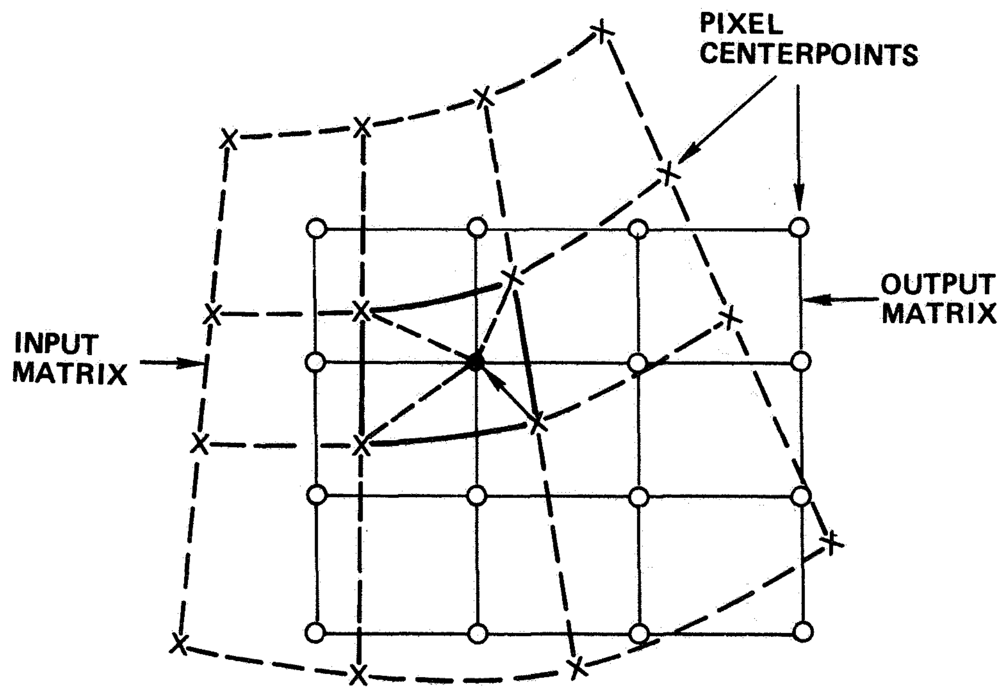


Figure 11. Geometric Correction Techniques

The image registration functions are specified in the block diagram. The correction determination box accepts scan duration and ephemeris information from the Thematic Mapper and GPS receiver, respectively. Alignment information is periodically furnished to this box from the ground. The correction determination box uses this information to determine attitude commands and resampling parameters, and the appropriate header information giving the location of a given image frame is also calculated. The resampling box accepts the correction parameters and performs the appropriate resampling and data formatting of the radiometrically corrected data. The resampling box should consist of custom-designed hardware because of the speed with which the processing must be performed. (See Figure 12.)

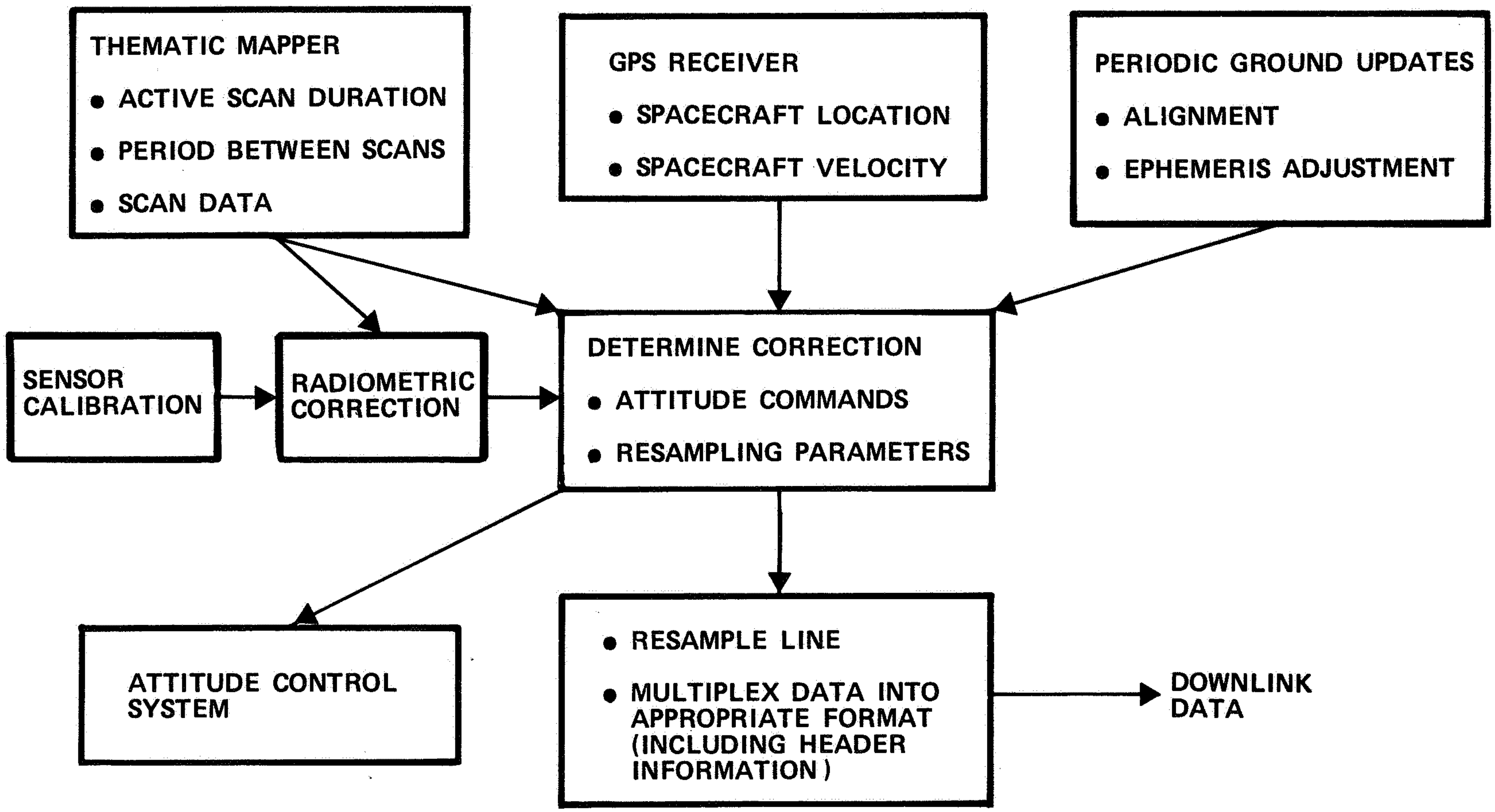


Figure 12. Onboard Processing Functional Block Diagram